RESEARCH ARTICLE

Assessing agro-ecological practices using a combination of three sustainability assessment tools

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HIGHLIGHTS

- **The performance of 131 farms in 15 farming systems were assessed by applying three sustainability assessment tools, namely SMART Farm Tool, Cool Farm Tool, and COMPAS.**
- **Agro-ecological farms generally perform better than conventional farms with regard to biodiversity and water quality.**
- **Biodiversity performance can be improved overall by integrating nature conservation efforts and targeted promotion of species on farms.**
- **While some agro-ecological practices lead to reduced greenhouse gas emissions, in certain contexts, some practices can increase the energy use of the farms.**
- **No clear patterns of the economic performance between conventional and agro-ecological farms are visible.**

KEYWORDS **agro-ecology, agro-ecological farming practices, sustainability assessment tools, SMART Farm Tool (RRID:SCR_018197), Cool Farm Tool**

Abstract

The alignment of the environmental, economic and social sustainability of farms is necessary for enhancing the provision of public goods in farming. This study combines the use of three tools for the assessment of farm sustainability. It provides first insights into the sustainability performance of farms at different stages of agro-ecological transitions in 15 case studies covering a range of different farming systems across Europe. Each case study reflects a different transition

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towards agro-ecological farming. The tools applied were COMPAS (an economic farm assessment tool); Cool Farm Tool (a greenhouse gas inventory, water footprint and biodiversity assessment tool); and the SMART Farm Tool (a multidimensional sustainability assessment tool).

First results of the use of combined sustainability assessments deepen the understanding of different farming systems. Sustainability performance varies greatly between farms, but overall, agro-ecological farms tend to enhance biodiversity and water quality. For soil quality, no clear patterns could be identified. The same applies to economic performance at different stages of the agro-ecological transition. Quality of life was generally rated medium to high on all investigated farms. The combined sustainability assessment enabled the identification of areas for further policy development.

Aligning the tools required harmonising definitions, simplification and assumptions with regard to the input data of the tools.

1 Introduction

The sustainability of farming needs to be enhanced to enable a sustainable food supply for a growing global population while remaining within the planetary boundaries (Campbell et al., 2017; Willett et al., 2019; EEA/FOEN, 2020; Pe'er et al., 2020). Given that the co-provision of public and private goods frequently remains imbalanced and not sustainable at a farm or farm systems level, agro-ecological practices are gaining increasing attention from practitioners and policy-makers (Duru et al., 2015; IPES-Food, 2016; Wezel and Bellon, 2018; HLPE, 2019). Such agro-ecological practices aim at supporting sustainable food production "while being based on various ecological processes and ecosystem services" (Wezel et al., 2014), for example, by substituting synthetically produced inputs with biological alternatives or restoring healthy agro-ecosystems.

The agro-ecological transition of farming systems implies adopting agro-ecological practices. It is linked to the ecosystem services these practices can provide (Altieri et al., 2017; Prazan and Aalders, 2019). There is a wide set of agro-ecological practices with varying degrees of application. A common way to classify them is according to the efficiency, substitution and redesign (ESR) framework, which was first introduced by Hill and MacRae (1996) and which describes different transition stages towards sustainable agriculture (see also Wezel et al., 2014). More specifically, agro-ecological practices may enhance the efficiency of conventional practices (e.g. the precision application of mineral fertilisers), substitute inputs (e.g. applying organic instead of mineral fertiliser), or redesign conventional approaches (e.g. introducing green manure; see Prazan and Aalders, 2019).

However, transitions towards diversified agro-ecological systems remain slow. To some extent, this can be attributed to the challenge of tackling the key dilemma of securing the economic and social sustainability of farms while providing public goods, such as environmental benefits (see, e.g. Otero et al., 2020). This is despite significant political efforts: 40 % of the European Union's 2014-2020 budget was allocated to the Common Agricultural Policy (CAP) (European Parliament, 2020). Yet, questions have been raised over the effectiveness of the underlying policy instruments aiming at enhancing the environmental state of agriculture (Pe'er et al., 2014, 2017, 2020; European Court of Auditors, 2017; Leventon et al., 2017). Despite recognition of the importance of agro-ecological practices for enhancing farm sustainability, identifying and integrating appropriate solutions is challenging and differs across contexts.

European farm-level data are insufficient for capturing agricultural sustainability (Kelly et al., 2018), however, assessment tools exist which can be used to determine the sustainability performance of farms (e.g. Arulnathan et al., 2020; Coteur et al., 2020; Janker and Mann, 2020). For such tools, the term sustainability assessment tools (SAT) is used in this paper if they cover at least one dimension of sustainability. The way they are constructed and the aspects of sustainability they investigate differ significantly (Coteur et al., 2020). The selection of a suitable tool is determined by factors that include the purpose of application as well as thematic and geographic scope (see e.g. Arulnathan et al., 2020; Coteur et al., 2020; Schader et al., 2014). A single SAT is unlikely to capture all of the relevant aspects of sustainability (Gasparatos et al., 2008). A more effective approach for assessing complex systems is to combine the use of different tools (de Olde et al., 2017).

This paper has two aims: i) to explore the potential and challenges of applying different SATs in parallel to assess farm sustainability in different farming systems and ii) to provide first insights into the sustainability impacts of agro-ecological practices implemented across Europe.

A set of different SATs were applied alongside each other (hereinafter called 'combined sustainability assessment'). The intended output was an overview of farm sustainability while also providing an in-depth assessment of at least one environmental topic, and of economic aspects.

To gain insights into all sustainability dimensions with an emphasis on the environmental and economic aspects, three state-of-the art tools were selected: SMART Farm Tool (hereinafter referred to as SMART), COMPAS, and Cool Farm Tool (CFT). SMART is a multidimensional sustainability assessment covering a broad range of sustainability topics. COMPAS covers the economic performance of farms. CFT is a greenhouse gas (GHG) inventory, water footprint and biodiversity assessment tool. Used in combination, the semi-quantitative SMART results are complemented with quantitative evidence obtained from applying COMPAS and CFT.

In the research work reported here, the three SATs were applied to 131 farms in 15 farming systems (case studies). Each of the farming systems comprises farm groups at different stages of agro-ecological transition which are represented by the assessed farms.

The selection of case studies and farms as well as the application of the SATs are described in detail. First insights are provided on how different types of farms perform in relation to core sustainability topics: GHG emissions, biodiversity, soil quality, water quality, productivity/farm income and quality of life. The identified patterns and trends are discussed in relation to relevant literature. The paper also reflects on the role of the current study for informing future policy development as well as some methodology matters.

2 Material and methods

The three SATs which were applied and the combined sustainability assessment are described below, followed by a description of their use in 15 case studies across Europe.

2.1 Description of the three sustainability assessment tools and the combined sustainability assessment

2.1.1 SMART

SMART (Sustainability Monitoring and Assessment RouTine; RRID:SCR_018197) is an instrument for analysing the sustainability of farms. SMART is considered to be among the most comprehensive SATs for undertaking sustainability assessments, delivering on seven of the eight Bellagio Sustainability Assessment and Measuring Principles (see Arulnathan et al., 2020; Pintér et al., 2012). So far the tool that has been used to assess 4,300 farms in 28 countries. It is based upon the globally recognised Sustainability Assessment of Food and Agriculture systems (SAFA) guidelines (FAO, 2013; Schader et al., 2016).

The four sustainability dimensions of SAFA are organised into 21 themes representing essential elements of sustainability and 58 subthemes (*Figure 2*, on the following page). Themes and subthemes are defined by goals and specific objectives, respectively. Each subtheme has SMART indicators which are associated with measurements relevant to achieving goals.

At its core, the SMART tool performs a multi-criteria analysis (MCA) that makes use of expert derived weights to aggregate indicators of subthemes. The subtheme scores range from 0 % (worst) to 100 % (best), and are mapped onto a colour scheme with five underlying categories of goal achievement (*Figure 1*).

2.1.2 COMPAS

COMPAS (Comparative Agriculture System Model) is a comparative, static, process analytical model used for detailed assessments of economic and technological changes at farm level. The model uses either data from the Farm Accountancy Data Network (FADN) or data that were specifically collected in farm surveys. Farm data are complemented by normative data from farm management handbooks, e.g. regarding energy use of individual machinery or in case detailed accounting records cannot be obtained in full. The data are processed to calculate technical and monetary input-output coefficients of individual production processes (i.e. crops or farm animals). Each production process can be examined in greater detail, e.g. comparing different production intensity levels or field plots.

The output comprises the intermediate indicators of Total Output and Total Intermediate Consumption as well as the key indicators Net Value Added, Farm Net Value Added per Agricultural Work Unit, hereinafter referred to as labour productivity, Net Farm Income, and the gross margins of the crop and livestock products. The process of calculations of all output indicators follows the FADN definition (FADN, 2018).

2.1.3 Cool Farm Tool (CFT)

CFT is an online SAT used to estimate the environmental impacts of food production (CFA, 2019a). The tool estimates on-farm GHG emissions from crops and livestock (Hillier et al., 2011). It consists of a generic set of empirical models of Tier 1, Tier 2, and simple Tier 3 approaches to estimate full farm-gate product emissions (see IPCC, 1997, for a definition of Tiers for GHG estimation in national inventories). The biodiversity module, which was released in 2016, is based on the Gaia biodiversity yardstick (CFA, 2019b; CLM, 2019) and covers the assessment domains of farmed products, farming practices, large habitats, small habitats, livestock, crop and variety, soil fauna, beneficial invertebrates, arable flora, wetland and aquatic flora, woodland flora, arable birds, woodland birds, aquatic fauna, grassland flora and grassland birds.

Each section of CFT was designed to enable farmers to adjust the entered data to obtain insights into the potential reductions in emissions that can result from changing farm management practices. Its global applicability has led to 9,000 users in numerous supply chains, covering 118 countries.

2.1.4 Combined sustainability assessment

Each of the three SATs uses slightly different input data and operates with different types of indicators and outputs, which can be aggregated at different levels. *Table 1* provides a summary of how the three SATs assess the core sustainability topics of GHG emissions, biodiversity, soil quality, water quality, productivity/farm income and quality of life.

The focal points of the tools vary with respect to the level of assessment. The approach of CFT is centred on the assessments of single farm enterprises, COMPAS is based on data from farm enterprises and of the whole farm, and SMART is mainly focused on data at the farm level (see *Table 1*). Data were integrated at the farm level to align outputs of the three

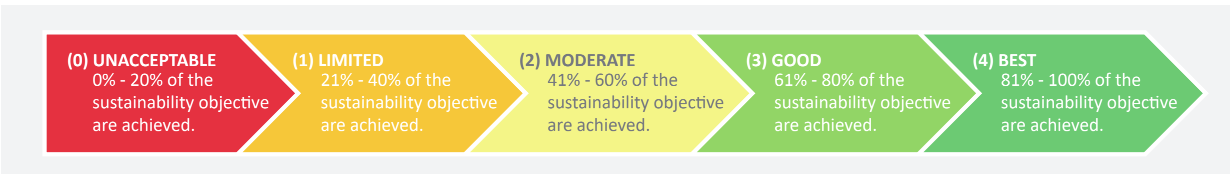

FIGURE 1
The five rating categories of SMART describing the degree of goal achievement in each subtheme

tools in the combined assessments. For CFT, the different emissions from farm enterprises were summed up in a dedicated MS Excel file. For COMPAS, only the farm level indicators were calculated by summing up data from the different farm enterprises.

The ability to represent the local context depends on the level of detail of the SAT. For example instead of selecting a locally occurring crop species (e.g. triticale), a more common crop species (e.g. wheat) had to be selected in one case. With this varying degree of detail between the tools, the input data needed to be aligned.

To streamline the simplifications described above and to align the input data, a Microsoft Excel tool for the data collection for all three tools was developed. This tool supported data entry using automated mechanisms, such as the conversion of data on fresh weight of livestock feed into dry weight (needed for CFT) based on conversion factors from feedipedia.org (Sauvant et al., 2013).

GOOD GOVERNANCE					
CORPORATE ETHICS	Mission Statement	Due Diligence			
ACCOUNTABILITY	Holistic Audits	Responsibility	Transparency		
PARTICIPATION	Stakeholder Dialogue	Grievance Procedures	Conflict Resolution		
RULE OF LAW	Legitimacy	Remedy, Restoration & Prevention	Civic Responsibility	Resource Appropriation	
HOLISTIC MANAGEMENT	Sustainability Management Plan	Full-Cost Accountng			
ENVIRONMENTAL INTEGRITY					
ATMOSPHERE	Greenhouse Gases	Air Quality			
WATER	Water Withdrawal	Water Quality			
LAND	Soil Quality	Land Degradation			
BIODIVERSITY	Ecosystem Diversity	Species Diversity	Genetic Diversity		
MATERIALS & ENERGY	Material Use	Energy Use	Waste Reductn & Disposal		
ANIMAL WELFARE	Animal Health	Freedom from Stress			
ECONOMIC RESILIENCE					
INVESTMENT	Internal Investment	Community Investment	Long-Ranging Investment	Profitability	
VULNERABILITY	Stability of Production	Stability of Supply	Stability of Market	Liquidity	Risk Management
PRODUCT QUALITY & INFORMATION	Food Safety	Food Quality	Product Information		
LOCAL ECONOMY	Value Creation	Local Procurement			
SOCIAL WELL-BEING					
DECENT LIVELIHOOD	Quality of Life	Capacity Development	Fair Access to Means of Production		
FAIR TRADING PRACTICES	Responsible Buyers	Rights of Suppliers			
LABOUR RIGHTS	Employment Relations	Forced Labour	Child Labour	Freedom of Association & Right to Bargaining	
EQUITY	Non Discrimination	Gender Equality	Support to Vulnerable People		
HUMAN SAFETY & HEALTH	Workplace Safety and Health Provisions	Public Health			
CULTURAL DIVERSITY	Indigenous Knowledge	Food Sovereignty			

FIGURE 2
Dimensions, themes and subthemes of the Sustainability Assessment of Food and Agriculture systems (SAFA) guidelines. Source: adopted from FAO (2013)

TABLE 1
Comparison of tools in the project's focus topics. The "+" sign indicates that the number of indicators scale with the number of crops and livestock on the farm. For a complete list of indicators, see supplementary materials S1.

		Level		Indicator type (Bockstaller et al., 2015)			Assessment type	
Topic	**SAT**	**Crop/live-stock**	**Farm**	**Causal indicators**	**Predictive effect indicators**	**Measured effect indicators**	**Semi-quantitative**	**Quantitative**
Greenhouse gas emissions	SMART		X	74			X	
	CFT	X			5+			X
Biodiversity	SMART		X	72			X	
	CFT		X	27			X	
Soil quality	SMART		X	70			X	
	CFT	X	X	Topic not covered as a separate assessment, but the soil type (e.g. including parameters such as humidity) serves as an input data domain for GHG emission calculation. Soil fauna is one indicator of the CFT biodiversity assessment.				
Water quality	SMART		X	61			X	
	CFT		X	Topic not covered as a separate assessment, but land use and management (riverine vegetation, ponds etc.) were entered for biodiversity assessment.				
Productivity and farm incomes	SMART		X	48		2	X	
	COMPAS	X	X		7+			X
Quality of life	SMART		X	46			X	
	COMPAS	X	X	Farm income, which contributes to quality of life, is covered (see above).				

2.2 Case studies

The combined sustainability assessment was first applied in case studies in 15 European countries. This section describes how they were selected and how farms were sampled within each case study.

2.2.1 Case study selection

The study aimed to include a broad coverage of farming systems in Europe that are at different stages of agro-ecological transitions. In a first step, the local case study teams developed three proposals for case studies in their country. Prazan and Aalders (2019) document the initial selections which were based upon 19 characteristics such as the production type of farms, sustainability issue, agro-ecological practices, coverage of the value chain by farmers, network presence, level of cooperation, and the presence of innovative policy tools and/or market incentives. These proposed case studies were evaluated based on a reduced set of criteria: i) the presence of innovative policy or market incentives, ii) a high degree of cooperation amongst farmers (and other actors), and iii) the involvement of farms in processing and sales. The final set of selected case studies had to fulfil at least one of these criteria and was recommended to the local case study teams to decide upon together with the local stakeholders involved.

In the final step, representatives from EU-wide institutions validated the final selection of case studies presented in *Table 2*. The set of case studies represents a wide range of production activities and of climatic and ecological contexts of Europe. For each case study, the core dilemma to be addressed by agro-ecological transition was identified by the local research teams.

2.2.2 Selection of farms along the agro-ecological transition pathway

The farm sampling strategy aimed to select representative farms with different strategies and performance profiles along the agro-ecological transition pathway following the previously introduced ESR framework (*Figure 3*). Based on this framework and the farm typology developed by Prazan and Aalders (2019), a guideline provided instructions to local case study teams on how to select farms. The first dimension of the farm typology (farm production system according to FADN) served to focus the case study on a certain farm production system (dairy, mixed, perennial farms etc.) to ensure the comparability between the farms in one case study. The second dimension (agro-ecological practices) helped define case study-specific farm groups along the transition pathway for the farm quota sampling. The third dimension (socio-ecological system context) was used to further characterise these groups.

A total of 51 farm groups were examined in the 15 case studies. These groups are presented in *Table 3* according to their stage of transition. For example, in the Swiss case study, four farm groups are described: one group of conventional farms specialised in pig and dairy representing the current system in the case study area (Stage 0). The second group consists of organic farms specialised in pig and dairy representing the input substitution stage (Stage 1 in the Swiss case study). Two additional farm groups (organic farms with

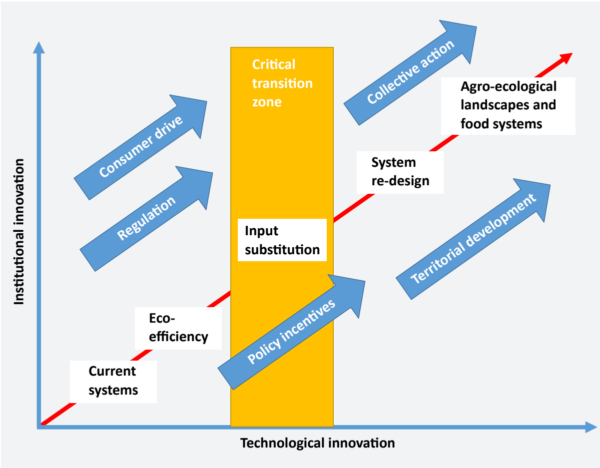

FIGURE 3
Representation of a transition pathway with different stages of transition. Source: Tittonell (2014), adapted by Prazan und Aalders (2019)

mixed special crops and extensive mixed livestock farms) represent the stage of system redesign, which equals Stage 2 in the Swiss case study.

Approximately 2.5 farms per farm group were then selected on average for the assessments (131 farms in total). The specific farms were chosen based on input from local stakeholders, such as farmer associations, local authorities, or rural advisory services. They provided the insights required for selecting farms representing the defined farm groups and established the contacts with the farmers. Half of the farm groups defined along the transition pathway (1st stage and 2nd stage in *Table 3*) are certified as organic. Although agro-ecology is not defined by a standard or a certification, organic farming can be still seen as a laboratory for ecological innovation (Tittonell, 2014) and, consequently, overlaps significantly with agro-ecological practices (Migliorini and Wezel, 2017).

TABLE 2
Overview of case studies and their dilemmas, which frame the development of practice-validated strategies for agro-ecological transitions. For each case study, the geographical scope is provided by referring to the level of the Nomenclature of Territorial Units for Statistics (NUTS).

Country	Case study dilemma	Geographical scope (NUTS level)
Austria (AT)	Increasing carbon sequestration in soils and soil quality without losing economic viability of arable farms	NUTS 3
Czech Republic (CZ)	Reducing soil degradation without losing economic viability of arable farming	NUTS 3
Germany (DE)	Reducing pressure on ecosystem (water, soil, biodiversity) without losing economic viability	NUTS 3
Finland (FI)	Reducing environmental impact of dairy farming without losing economic viability	NUTS 3
France (FR)	Reducing dependency of external fertilisers and pesticides without losing economic viability	NUTS 1
Greece (GR)	Reducing use of agro-chemicals in fruit production without losing economic viability	NUTS 3
Hungary (HU)	Improving soil quality without losing economic viability	NUTS 0
Italy (IT)	Increasing diversification without reducing profitability	NUTS 2
Lithuania (LT)	Enhancing economic viability and competitiveness of dairy without intensifying production	NUTS 1
Latvia (LV)	Enhancing economic viability and competitiveness of dairy without increasing pressure on water and biodiversity	NUTS 2
Romania (RO)	Enhancing economic viability and competitiveness of small-scale farming without damaging cultural landscape and biodiversity	NUTS 1
Spain (ES)	Improving economic resilience without increasing pressure on the ecosystem	NUTS 1
Sweden (SE)	Diversifying specialised ruminant livestock farms to include more crops for direct human consumption without losing economic viability	NUTS 0
Switzerland (CH)	Reducing water eutrophication and ammonia emission from intensive livestock keeping without losing economic viability	NUTS 1
United Kingdom (UK)	Producing public goods while maintaining viable production of private goods, and securing economic and social sustainability at a farm level	NUTS 2

TABLE 3
Overview of the farm groups in the case studies and their classification along the transition pathway.
Stage 0 comprises farms which are not agro-ecological. The term ‘in transition’ used in the table refers to farms in transition to input substitution by applying some practices used in organic farming. ‘Org.’ stands for organic farming, ‘Conv.’ for conventional farming.

		Stage on the agro-ecological transition pathway		
	Main agro-ecological practices	Stage 0 (S0)	1st stage	2nd stage
AT	Soil management (humus formation)	Conv. fruit farms	S0 + participating in humus project	Org. fruit farms participating in humus project
		Conv. mixed livestock (pig) arable farms	S0 + participating in humus project	Diversified mixed livestock (pig, poultry, cattle) arable farms, participating in humus project
CZ	Livestock density/ soil management	Conv. specialised dairy	Org. specialised dairy	
FI	Livestock density/livestock diversity	Conv. specialised dairy	Org. dairy farms (incl. some more diversified)	
			S0 + biogas project	
FR	Weed, pest and disease control	Conv. perennial (wine)	Partially org. perennial (wine)/ in conversion	Demeter perennial (wine)
DE	Fertiliser and soil management, flower/buffer strips, crop diversification	Specialised arable farms (with minor pig systems)	S0 + some agro-ecological practices	
GR	Integrated crop management (ICM, fertiliser and soil), pest control (mating disruption)	Fruit farms without ICM or mating disruption technique	Fruit farms with ICM or mating disruption technique	Fruit farms with ICM and mating disruption technique
HU	Soil management (erosion)	Arable farms	S0 + reduced tillage	No-till arable farms
IT	Fertiliser management/soil management	Intense perennial (wine)	Org. perennial (wine)	Org. perennial (wine) with advanced soil management
LV	Livestock diversity	Conv. specialised dairy	S0 + grazing	Org. specialised farms
LT	Livestock diversity		Extensive specialised dairy farms	Extensive mixed dairy
			Org. specialised dairy	
RO	Livestock density/fertiliser management/weed, pest and disease control	Conv. specialised dairy	Org. specialised dairy	
		Conv. cattle rearing and fattening	Cattle rearing and fattening in transition	
			Mixed fruit/arable farms in transition	Org. mixed fruit/arable farms
ES	Crop spatial diversity	Conventional arable farms	Arable farms in transition	Org. arable farms
SE	Livestock diversity/density	Conv. specialised beef farms	Org. and/or more diversified dairy farms	Org. diversified production of beef or lamb and crops
			Org. and/or diversified beef or lamb farms	
CH	Livestock diversity/density	Conv. specialised livestock farms (pigs, dairy)	Org. specialised livestock farms (pigs and dairy)	Org. mixed special crop–livestock farms
				Org. extensive mixed livestock farms
UK	Fertiliser and soil management and pest control	Conv. arable farms	Mixed farms in transition	Org. arable farms
		Conv. mixed farms		Org. mixed farms

2.2.3 Data collection and evaluation

The data collection and evaluation was mainly done by the local case study teams with support of a SAT coordinator for each of the three tools (see *Figure 4*).

To create a common understanding of the assessment process among the case study teams and to streamline farm assessments, a guideline was provided to set out the steps needed for the farm assessment, such as reducing the assessment time by omitting farm enterprises of limited relevance in the operation of CFT and COMPAS. The guideline was accompanied by seven webinars and a six-day, face-to-face field training course.

The farm visits listed in *Figure 4* each lasted between three and four hours. Throughout the whole process, the local case study teams verified data with the SAT coordinators by i) drawing attention to any uncertainties about data quality in a dedicated online forum and ii) incorporating the feedback from the spot check of their data conducted by the three SAT coordinators. A separate guideline was provided for the data quality review process and result evaluation.

In a next step, the results were analysed by the local case study teams by comparing the results of the farm groups along the transition pathway with similarities and differences relating to the core sustainability topics. This approach to result evaluation aimed at i) accounting for the local context of each case study and ii) focusing the analysis of the more than 10,000 data records. To enable consideration of context, causalities, and potential data issues, a section of the guidelines framed the comparison between farm groups with the following questions (summarised):

- How do farm groups compare to structural farm data available for the region (e.g. FADN data)?
- What are the causalities or contributions of different processes in the SATs behind the observed patterns?
- How does the sample size affect the comparison?
- How does the farm type affect the comparison?
- What are other potential limitations for drawing conclusions?

The guideline also provided a structure for reporting the results (see supplementary materials S2).

In the final step, all case study reports were iteratively summarised for each core sustainability topic (see Section 2.1.4) accounting for patterns of similarities and differences between the farm groups.

The aggregated findings in pesticide use, fertiliser use, soil management, quality of life, and income volatility were complemented with a central data analysis in SQL Server Management Studio to query SMART indicator data across several case studies and MS Excel to further evaluate the query results (e.g. comparing conventional and agro-ecological farms).

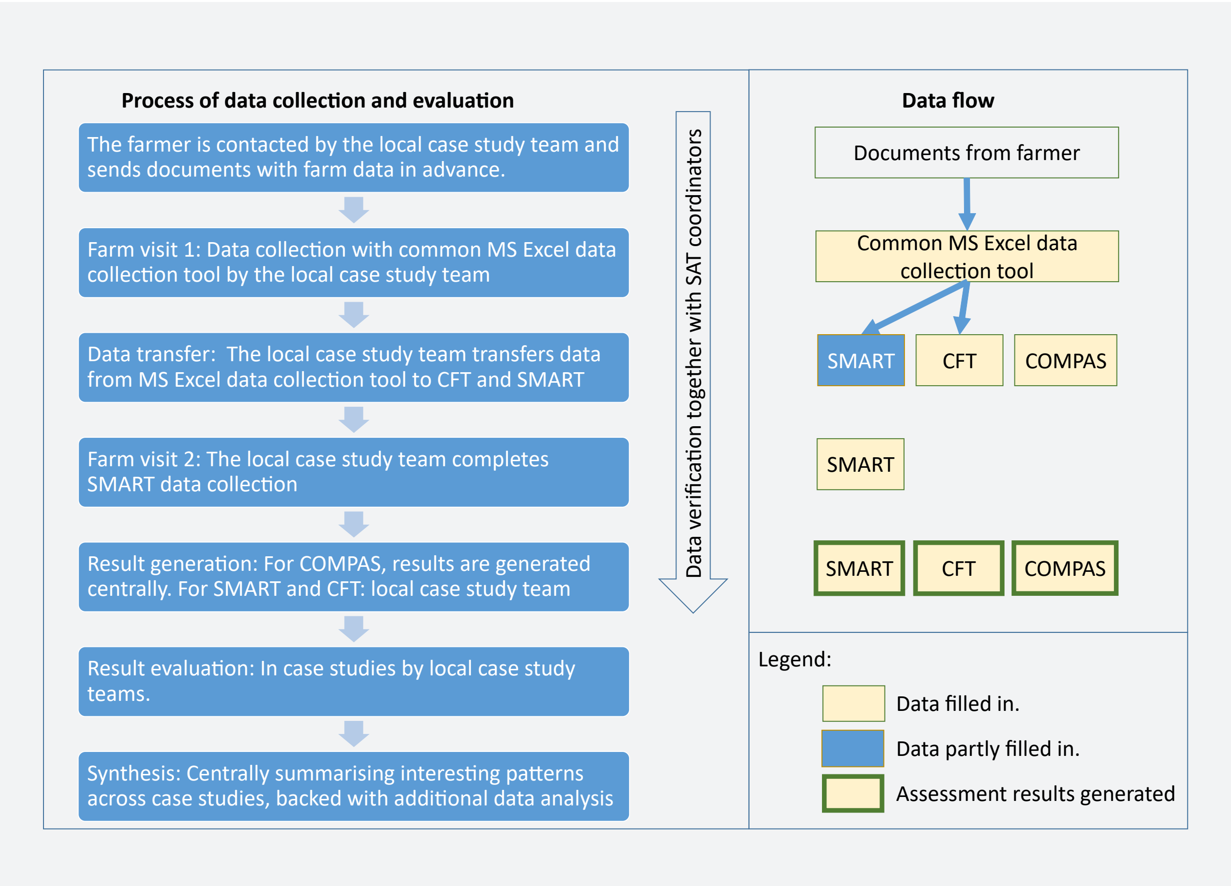

FIGURE 4
Data collection and evaluation workflow

3 Results and discussion

The patterns and trends identified from the application of the SATs in the case studies are summarised in *Table 4*. The results are based on the analysis of similarities and differences between the defined agro-ecological farms (i.e. farms in the 1st and 2nd stage of agro-ecological transition, n=84) and their conventional counterparts in the case studies (n=47, *Table 3*). These comparisons were conducted within the context of each case study and, in selected areas, explored in all or several case studies (see section 2.2.3). The observations are summarised in the following sections.

The farm groups are a simplification of the wide range of agro-ecological transition perspectives in the case studies. The implications of this heterogeneity are discussed in Section 4.2. The first results are accompanied by the code of the countries representing those case study reports in which the corresponding findings were explicitly mentioned. The underlying data is provided in the database compiled by Landert et al. (2019).

The results described below refer to SAT performance ratings, illustrated in *Figure 5* by SMART results. For example, a higher rating for the SMART subtheme Soil Quality implies a better performance of farms in aspects related to soil quality (see section 2.1).

3.1.1 Greenhouse gas emissions

In the case studies, the production systems largely determined the GHG emissions of farms and the potential for mitigation. The level of agro-ecological transition appears to generally have less impact. Nevertheless, for the perennial systems of France and Greece, the results of CFT suggest that agro-ecological practices can lead (in some cases) to an increase in GHG emissions. Reasons for such increased emissions are, e.g. the increased fuel use for mechanical weeding (FR) and drip-irrigation in the case of some Greek conventional and agro-ecological peach farms, which leads to increased energy use compared to the flood irrigation of the other farms in the sample.

In arable farming, the SAT assessments identified the use of nitrogen (N) fertiliser as the main contributor to emissions because of nitrous oxide (N2O) and emission from the production of synthetic fertilisers. This is reflected in the CFT results for the Swiss case study, in which the contribution of N-fertiliser application to crop and grassland-related GHG emissions was 36 % (on average) across all farm groups. Some of the agro-ecological farm groups investigated used less N-fertiliser, which was reflected in lower GHG footprints per hectare in CFT and a higher SMART score, compared to the more conventional counterparts: In Spain, on average the agro-ecological farms used 107 kg N ha^{-1} of agricultural area (180 kg N ha^{-1}in case of conventional farms), while in Switzerland these farm groups used an average of 89 kg N ha^{-1} (169 kg N ha^{-1} in case of conventional farms). The CFT assessment shows that soil conservation techniques in arable systems contribute (temporarily) to GHG mitigation (AT, CH, IT, HU). Yet, the difference in the average share of agricultural land under reduced tillage between agro-ecological and conventional farm groups was small across the four case studies: 62 % in case of agro-ecological farms versus 58 % in case of conventional farms. Despite the similar share of reduced tillage, the weed control differed: the conventional group did not use undersown cover crops at all, compared to an average share of 6 % area with undersown cover crops on the agro-ecological arable land. Also, the average share of arable area where catch crops are grown was only 5 % on conventional farms compared to 12 % in the case of agro-ecological farms. The SAT results also reveal lower pesticide use on the agro-ecological farms (LV, ES), which reduces GHG emissions to a small extent on agro-ecological farms.

TABLE 4
Summary of identified patterns and trends

Sustainability topic	Identified patterns and trends
Greenhouse gas (GHG) emissions	Different agro-ecological field management practices have a reducing effect on the total GHG emissions of farms. Some agro-ecological practices increase total farm emissions.
Biodiversity	Biodiversity scores are mainly determined by farming practices. Agro-ecological farm groups tend to show higher levels of biodiversity than their conventional counterpart. However, agro-ecological farming practices are not necessarily associated with measures designed to promote biodiversity.
Soil quality	Farm type (conventional or agro-ecological) did not have a consistent effect on SAT scores for soil quality. As one reason, some practices are applied by all farm types such as determining soil fertiliser requirements which contributes positively to the soil quality scores.
Water quality	Agro-ecological farm groups show higher scores for water quality, particularly due to reduced use of pesticides, fertilisers, and practices such as erosion management.
Productivity and farm incomes	The majority of farms generate positive income, but subsidies (including direct and other payments) represent a major proportion of the farm income in all countries. As such, SAT results show no clear patterns between labour productivity, farm income and the stage of agro-ecological transition.
Quality of life	The quality of life is generally high on all farms, whether they are oriented towards agro-ecological practices or not. A lower degree of mechanisation (and therefore higher physical workload) impacts quality of life negatively in some case studies.

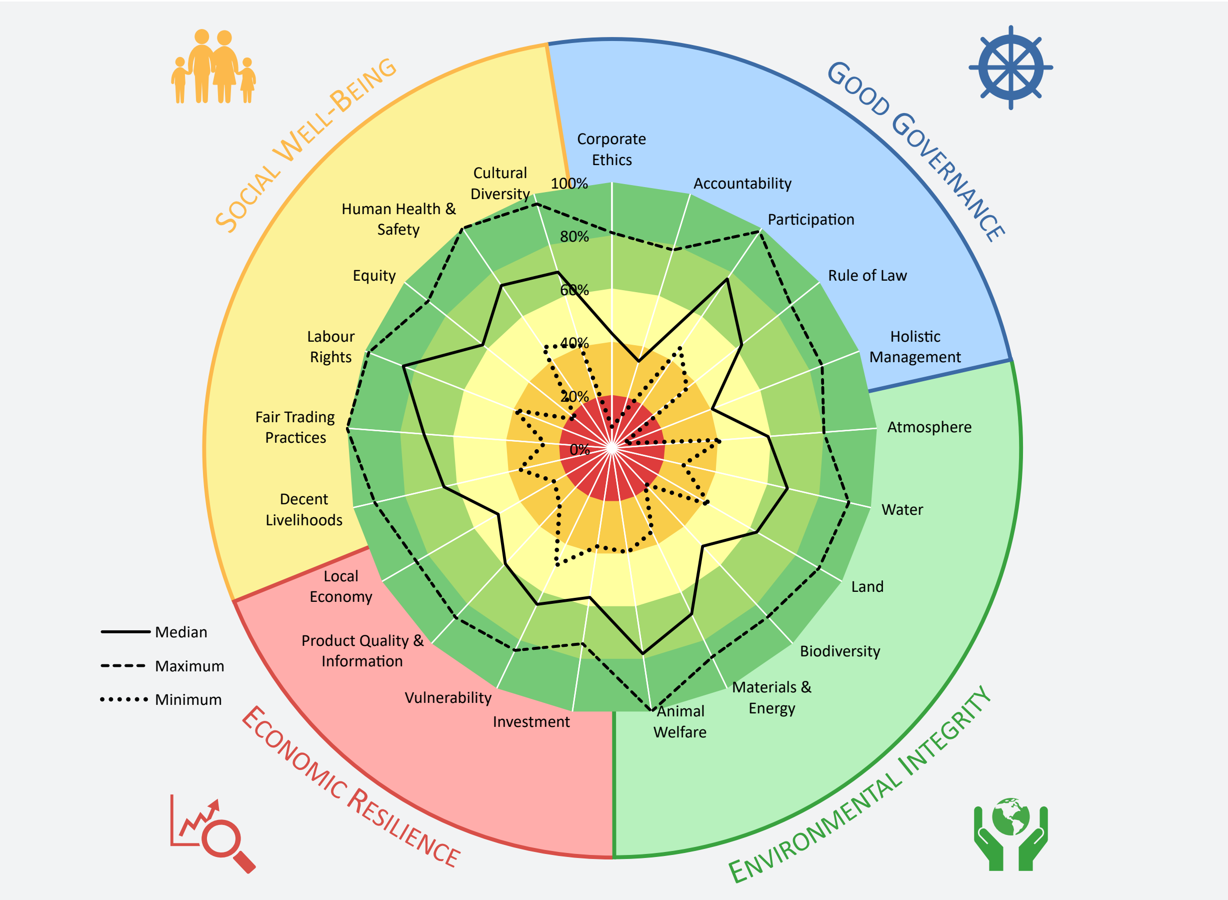

FIGURE 5
Ratings for the 21 SMART themes across all case studies

3.1.2 Biodiversity

SATs cover different aspects of biodiversity, including genetic, species, and ecosystem diversity (SMART, see Section 2.1.1) or, in the case of CFT, scores that express the impact of farming on certain biotic communities, such as soil fauna (see Section 2.1.3). *Figure 6* shows the scores for soil fauna across the farm groups in the case studies.

With regard to biodiversity, CFT and SMART rank agro-ecological farm groups higher than their conventional counterparts in most cases. Across all case studies, agro-ecological farms have an average rating of 54 % in SMART, whereas conventional farms score 42 %. The SATs yield higher biodiversity scores because of differences in farming practices, such as soil conservation practices (HU), biodiversity conservation (DE), a higher diversity of livestock, and crop rotation elements (CH, ES, IT, LV, RO). In the latter case, agro-ecological farms across all case studies exhibit, on average, a minimum number of 3.71 crops in the rotation compared to 3.48 on conventional farms. In addition to crop diversity, also the cultivation on small plots (RO), the application of less N-fertiliser (CZ, CH, ES, RO, UK) and less pesticides (CH, CZ, ES, GR, RO, SE, UK; number of active ingredients) lead to higher biodiversity scores on agro-ecological farms. The use of less pesticides in the cited cases is also reflected across all

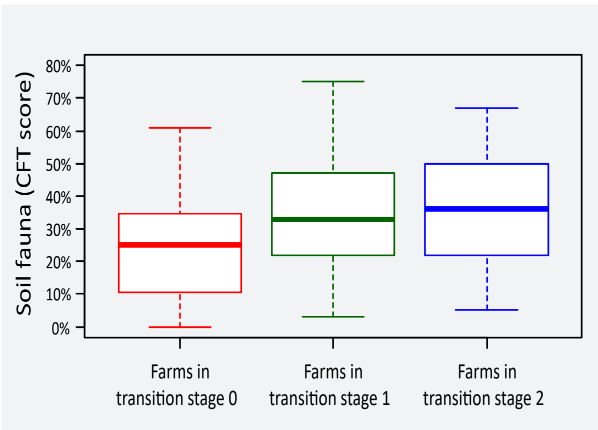

FIGURE 6
Median soil fauna biodiversity score provided by CFT (0 – 100 %) including quartiles, minimum and maximum for farms in the case studies (excluding Finland and Spain where no CFT biodiversity data is available) at the three agro-ecological transition stages (see Table 3)

case studies by a lower average number of active ingredients being used on agro-ecological farms compared to conventional farms. Correspondingly, agro-ecological farms (including 40 farms with no pesticides registered) scored better in the SMART indicators with regard to the toxicity attributes of pesticides, such as acute (inhalation) toxicity, chronic toxicity, and toxicity to bees and aquatic organisms. The active ingredients registered on agro-ecological farms are, on average, less persistent in water (248 days versus 282 days of half-life time in the case of conventional farms). However, the greater use of copper on agro-ecological farms led to a high average persistence of pesticides in soils (243 days [104 days without considering copper] of half-life time versus 237 days for pesticides used on conventional farms).

It appears that agro-ecological farming practices do not necessarily correlate with targeted measures to promote biodiversity or the creation of large habitats (AT, CZ, LT, LV): The median CFT score for large habitats equals 2 % for agro-ecological farms (on a scale from 0 % to 100 %). Results from SMART show that the share of agro-ecological farms which undertake targeted promotion (of one group) of species (23 %) is even lower than for conventional farms (33 %).

3.1.3 Soil quality

While the CFT scores for soil fauna (an indicator of the biodiversity assessment) suggest that agro-ecological farms perform better (*Figure 6*), the SMART results did not show clear patterns between the groups of conventional and agro-ecological farms. The assessments of soil quality and soil fauna by the two SATs are mainly based on farming practices and land use, with additional topics, such as soil pollution and erosion, assessed by SMART (see supplementary materials S1).

While indicators in these different topics all similarly contribute to the final SMART soil quality score, it was in some case studies positively influenced by the following agro-ecological practices: mulching (AT, FR), higher use (twice the level) of legumes in crop rotation in the agro-ecological group than in the conventional farm group (CZ), maintenance of grass cover between vine rows (FR, IT), undersown crops (CH, CZ), reduced till (AT), no-till (HU), reduced soil contamination due to pesticide use (LV, GR), or determining soil fertiliser requirements (LV). The higher share of legumes can be identified across all case studies (on average, 10 % on conventional arable land versus 17 % on agro-ecological farms). The farm groups also differed with regard to the undersowing of crops (3 % on average on conventional arable land versus 12 % on agro-ecological farms). Although the application of reduced tillage varied less between the farm groups, it is still substantial (36 % on average on conventional agricultural area versus 45 % on agro-ecological farm land). The same applies to the green cover outside the growing period (50 % on average on conventional arable land versus 65 % on agro-ecological farms).

Composting was not explicitly mentioned as playing an important role. Correspondingly, only 14 % of agro-ecological farms which apply organic fertiliser apply plant or livestock-based compost (15 % of conventional farms).

3.1.4 Water quality

Most agro-ecological farm groups perform better across the case studies, particularly due to a reduced use of pesticides (AT, CZ, GR, LV), fertilisers (AT, CH, CZ, GR, LV, LT, SE), and improved erosion management (AT, CH). Overall, the median SMART scores for the farm groups in all case studies ranged between 60 % and 80 % (*Figure 7*).

Buffer strips along surface waters, an important measure of the current CAP, cross-compliance, and post-2020 CAP conditionality, contributed to a high SMART rating (CZ, HU).

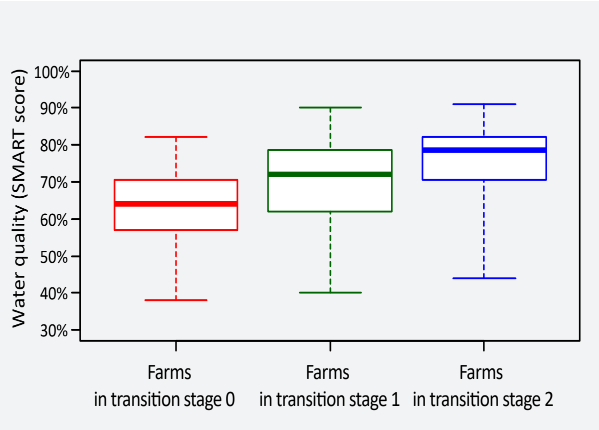

FIGURE 7
Median SMART scores of goal achievement for the subtheme water quality including quartiles, minimum and maximum, separately displayed by the three agro-ecological transition stages (see Table 3) in all case studies

3.1.5 Productivity and farm incomes

The majority of farms (95 %) generate positive net incomes with their crop and livestock farming activities in the reference year. This was true for 77 % of the conventional farms and 92 % of the agro-ecological farms over the last five years. However, subsidies represent a major share of the farm income in all countries. The SAT results show no clear patterns between labour productivity, farm income, and the stage of agro-ecological transition. In one case (AT), results from different SATs yield contradictory results, which reflects COMPAS's focus on economic performance in a particular year, compared to SMART tending to assess medium term economic resilience. In the Swiss case study, agro-ecological farm groups were reported to show lower labour productivity than their conventional counterparts. In other cases, higher subsidies (LV), sales through shorter supply chains (AT, FR, LT), or higher price premiums from organic farms (FR) contribute to the net farm income of agro-ecological farms.

3.1.6 Quality of life

With SMART scores ranging from 48 % to 92 % (average: 74 %), quality of life can be considered medium to high on all of the assessed farms. This suggests that agriculture provides viable livelihoods, i.e. modes of living that fulfil people's needs and expectations, although there are exceptions (RO). Reasons for the high scores are the profitability of farms and the generally high labour standards in Europe (CZ, ES, FR, SE), in spite of common characteristics, such as extra hours worked (see also section 4.1).

The results indicate scores of a slightly lower quality of life in some case studies for agro-ecological farms due to less mechanisation, resulting in higher physical workload (CH, ES, LV).

3.1.7 Integrated perspective on sustainability issues

The combined sustainability assessment made it possible to identify some initial sustainability synergies and trade-offs in the case studies, for example, in Spain, where farms with a higher biodiversity performance have lower GHG emissions. In the Latvian case study, mineral fertiliser and pesticide applications are the reason for synergies between efforts to increase biodiversity and improve water quality. In place of mineral fertilisers, organic farms in Latvia often use perennial grasslands with nitrogen-fixing legumes to maintain soil fertility. In Greece, the agro-ecological practices used led to synergies between efforts relating to soil and water quality.

Two case studies explicitly reported trade-offs between the economic performance of the farm and biodiversity (CH, CZ). In contrast, the Italian case study showed that more specialised and economically viable winemakers implement more agro-ecological practices. However, a transition to agro-ecological practices may also result in trade-offs in the environmental dimension. In some cases, GHG emissions rise due to higher energy use, caused, for example, by increased mechanical weeding or energy-demanding irrigation (FR, GR). In the Swedish case study, greater plant protein production meant more intensive arable farming, which led to a decrease in performance with regard to soil quality.

4 Discussion

4.1 Patterns and trends

The combined sustainability assessment showed what agro-ecological practices mainly contributed to the core sustainability topics investigated. These practices led to generally higher scores of agro-ecological farm groups in the case of biodiversity and water quality, compared to their non agro-ecological counterparts. In the other four sustainability topics investigated, the results imply that a variety of factors, which are independent of agro-ecological transition, determine the sustainability performance of farms, e.g. the farm production system. In addition, the results suggest that agro-ecological practices can, in certain contexts, also have negative impacts on certain sustainability topics.

Most examples of such negative impacts are related to greenhouse gas emissions and comprise practices such as mechanical weeding in French organic vineyards. The associated increase in fuel consumption is reported for other organic production systems by Smith et al. (2015). On arable farms, soil conservation techniques were a key factor for reducing greenhouse gas emissions. Sanz-Cobena et al. (2017) confirm this positive impact in their review for the Mediterranean area. Yet, they also point out that the rate of carbon sequestration is likely to decrease over time (Sanz-Cobena et al., 2017). In addition, there are general uncertainties related to the potential of no-till to increase soil carbon stocks (Ogle et al., 2019).

In the case of the Hungarian case study, no-till led to higher CFT soil biodiversity scores. This positive effect in the model is confirmed in field studies (e.g. Adl et al., 2006). The higher number of crops on farmland and the smaller plot size had a positive effect on the biodiversity scores. Sirami et al. (2019) identified plot size to be a key determinant for multitrophic diversity in their study of 435 landscapes across 8 regions of Europe and North America. They found that the effect of crop diversity on the multitrophic diversity varies depending on the extent of areas with semi-natural cover. In the pan-European study of Billeter et al. (2008), the crop diversity on farms had a positive impact on the diversity of three arthropod species groups. The authors also found a negative effect of high nitrogen fertiliser use (>150 kg N ha^{-1} $year^{-1}$) on plant species diversity and on the number of bird species. This provides another reason for the negative biodiversity ratings among the conventional farm groups: farms with a mean input in excess of 170 kg N ha^{-1} $year^{-1}$score lowest for the corresponding SMART indicator. A reduction in N input in the range below 25 kg N ha^{-1} $year^{-1}$is not considered by SMART.

The lower use of pesticides in agro-ecological farm groups (lower number of active ingredients employed) and the associated use of less hazardous pesticides also contributed to the higher SAT rating with regard to biodiversity. Again, these findings are identified in field studies as main factors influencing biodiversity, such as the pan-European study by Emmerson et al. (2016). Although the agro-ecological farms investigated perform well with regard to their farming practices, in several case studies they fall short in the provision of larger semi-natural habitats, which is another key aspect of how agriculture impacts biodiversity (Billeter et al., 2008).

Although agro-ecological practices have been identified to contribute to the soil quality in the case studies, no clear pattern was observed with regard to SMART ratings between conventional and agro-ecological farm groups. This somewhat counterintuitive observation can be explained by the fact that such practices are important for the calculation of the soil quality score of SMART, but other factors, such as land use, soil condition, or additional farming practices, have a similar importance in the calculation of the score. Consequently, these factors need to be looked at more closely in further steps of the data analysis in order to identify those practices, which can be improved on both, agro-ecological and conventional farms with regard to soil quality.

A further observation is that composting was not a common practice on agro-ecological farms in the case studies despite its potential to improve soil quality (Martínez-Blanco et al., 2013). This contrasts with the findings of Viaene et al. (2016) in which 87 % of the surveyed organic farmers used compost (in contrast to 14 % of the agro-ecological farms in this study). This large difference in use of composting cannot fully be explained by the variation between countries or regions. The use of compost seems also to vary between farms in the same case study. Generally, this shows that there is an untapped potential for policies and farm advice to promote composting and minimise barriers to its uptake.

Similar to findings for biodiversity, the SAT ratings for water quality were more negatively impacted by the N-application rate on conventional farms than agro-ecological farms. The use of fewer pesticides had positive implications for aquatic organisms. The rating effect of N-application rate is to be taken indicatively since the corresponding indicator does not consider agri-environmental factors such as climatic conditions, soil water content, crop type, soil type, or the use of catch crops, all of which are identified as important determinants for nitrate leaching by Beaudoin et al. (2005).

Although most of the farms were profitable during the reference year, the net farm income of conventional farms was shown to be slightly more volatile over time than that for agro-ecological farms. However, this pattern of income volatility does not seem to be general in nature, since Krause and Machek (2018) were not able to detect such a pattern in their comparison between Czech organic and conventional farms. Meuwissen et al. (2018) identified other factors that are important for income volatility, such as the country and farm production system. While in our study no overall patterns for farm income could be identified, Krause and Machek (2018) note that Czech organic farms tend to have a higher profitability (determined by the return on assets). This last finding is further underpinned by the meta-analysis of Crowder and Reganold (2015) on profitability of organic farms for 55 crops across 14 countries. Moreover, in the case of conventional arable farms in France, Lechenet et al. (2017) did not observe a general loss of profitability when reducing the use of pesticides. Yet, empirical evidence varies across studies, depending on the country and production system (Krause and Machek, 2018). The relevance of short supply chains and higher prices from premia for profitability has been confirmed in other studies (Crowder and Reganold, 2015; Hatt et al., 2016; Krause and Machek, 2018). On Swiss agro-ecological farms, the lower degree of mechanisation, the lack of innovative collaboration models (i.e. group farming), and the absence of short supply chains might all have been contributing reasons for the lower labour productivity.

The general profitability of the investigated farms directly or indirectly contributed to high ratings for some SMART indicators of the quality of life subtheme. In line with that, Besser and Mann (2015) found that farm income (measured by proxies of farm size and perceived financial situation) positively influences (to different extents) the relatively high work satisfaction of farmers in Switzerland and northern Germany (approximately 7 on a scale from 1 to 10). However, the relatively high scores for the SMART quality of life subtheme also stems from the fact that the used indicators rated European labour standards as high (also see section 4.2). In this study we could not identify clear differences between agro-ecological farms and conventional farms; however, there is some evidence for a higher satisfaction among organic farmers compared to conventional farmers in France (Mzoughi, 2014; Bouttes et al., 2020).

Throughout the analysis of the results, some synergies emerged. An example is the higher rationalisation and economic success in the Italian case study that led to the adoption of more agro-ecological practices for managing vineyards. This is similar to findings reported for vineyards in Portugal by van der Ploeg et al. (2019). In general, reducing fertiliser and pesticide inputs (given the limitations of generalizing such reductions, as discussed above) also leads to synergies between different aspects of sustainability (apart from the risk of increasing GHG emission due to higher fuel use related to mechanical weeding). Therefore, unsurprisingly, reducing the use of pesticides and fertilisers is at the core of the EU's Farm to Fork Strategy (European Union, 2020). The results of this study provide additional indications for policy priorities. For example, with respect to biodiversity, the lack of large habitats found in this study suggests a need for improving the embedding of conservation efforts in measures in the CAP post-2020, as recommended by groups such as the Alliance Environment (2019). By revealing a low level of diffusion of certain environmentally beneficial practices (such as composting), the results of this study provide indications on practices that could be incentivised under the new Eco-schemes in EU Member States.

4.2 Combined sustainability assessment framework and process

The approach taken in this study enabled the benefit of combining different perspectives on sustainability, as suggested by previous studies, such as Gasparatos et al. (2008). This combination of different perspectives allowed to relate the performance in the core sustainability topics with each other and therefore the identification of patterns of synergies and trade-offs.

With the exception of the underlying SAFA framework in the case of SMART, all SATs represent a top-down approach (Binder et al., 2010) with only partial involvement of stakeholders in their development. This contrasts with the recommendations of Arulnathan et al. (2020) and de Olde et al. (2017) to engage stakeholders in the development of such tools to increase their acceptance by end-users and to take local contexts into account. As a consequence, there is a trade-off between the desired global applicability of the SATs and how local context is accounted for. Coteur et al. (2016), Janker and Mann (2020), Röös et al. (2019), and others stressed the need for taking the local context into account, and Binder et al. (2010) confirmed that there are trade-offs between context applicability and standardisation in tools for benchmarking. This standardisation manifests itself, for example, in the SMART quality of life subtheme, in which some indicators reflect relatively low standards in comparison to those in the more developed European context. For example, fulfilling the International Labour Organisation Fundamental Principles and Rights at Work (ILO, 1998) tends to be embedded in the operation of all farms in European countries, which is reflected in the relatively high scores of the assessment.

As outlined in section 2.1.4, where necessary, the output of the tools was aggregated to the farm level to overcome problems of mismatches in scale. This step proved to be especially challenging when calculating greenhouse gas emissions, which was prone to errors of double accounting, for example, due to the use of common infrastructure for electricity or due to emissions from feed grown on the farm. These issues were underestimated and suggest a need for more emphasis on the methodology for this step in future projects and for the inclusion of specific indications in each tool on how these emissions from single farm enterprises may be aggregated to higher levels.

Apart from the issues arising from the different levels of assessments, the alignment of input data referred to in section 2.1.4 required simplifications and assumptions to address differences in concepts and to align the SATs to an interdisciplinary approach to data collection. The interdisciplinary approach represented a strength of this study since it is being widely accepted as the basis for advancements in sustainability issues, and the employment of assessment approaches is seen as beneficial for ensuring the plurality of views (de Olde et al., 2017). However, the interdisciplinary approach was also very demanding for both interviewers and farmers. This may have aggravated the common challenge of all models relying on empirical survey data, namely the risk of subjectivity (Biemer et al., 2013). Both the matching of a qualitative answer in the interview with one of the pre-defined answers in the questionnaire and the derivation of quantitative data together with the farmer were prone to this risk.

With the complexity associated with case studies in 15 European countries, this study was potentially vulnerable to heterogeneous assessments. Since the primary data evaluation was carried out separately in each case study (see section 2.2.3), the level of subjectivity within each case study should be the same. Nevertheless, comparisons across case study findings should be interpreted with caution since the exploratory approach of comparing the farm groups with regard to similarities and differences in selected topics (see section 2.2.3) yielded different focus points in the reporting by the case studies. Such inconsistencies may also stem from local adaptions of the data collection procedure that were necessary, e.g. how the interviews were conducted. In some case studies, due to long distances between farms, interviews were conducted in one session, which could have led to loss of concentration for the interviewer and the farmer.

Another reason for heterogeneous assessments was the definition of system boundaries: this mainly affected the calculation of the aggregated farm level greenhouse gas emissions for which it was possible, due to the high demand in interview time on diversified crop farms (> 5 elements in crop rotation), to leave out crops with a share of less than 10 % of the arable land. The same was true for diverse livestock farms (> 2 livestock species) with livestock accounting for less than 10 % of the total livestock units on the farm. The left-out livestock was also not considered for the economic analysis in COMPAS. These means of shortening the assessment time were applied to a varying degree across the case studies. This heterogeneity may have been caused because the mentioned cut-off criteria were not directly incorporated into the tools themselves (Arulnathan et al., 2020).

Apart from the limitations relating to combining the tools, the data collection and evaluation, another limitation of this study was that farms were sampled with quota sampling instead of random representative sampling, which was beyond its scope. Consequently, the small number of farms assessed in each case study is unlikely to be sufficient to cover the heterogeneity of farms within the farm groups. This introduced a degree of uncertainty in the comparisons that can be made between the sustainability performances of farm groups. To overcome this limitation, the possibility of integrating our approach into existing, representative farm information systems should be further explored. One example would be the FADN, which aims to be representative with regard to the FADN region, economic size and type of farming. This corresponds to the need identified by Kelly et al. (2018) of complementing FADN data with social and environmental indicators, although they also caution that the sampling concept of FADN needs to be reviewed when doing so.

5 Conclusion

The combined sustainability assessment indicates that the agro-ecological farms investigated contribute positively to biodiversity and water quality, whereas no clear pattern was observed regarding their impacts on soil quality. With regard to greenhouse gases, in some cases, agro-ecological farms have lower N-fertiliser application rates, which contributes to a reduction of emissions. However, a few agro-ecological practices also lead to higher emissions, for example, due to an increased use of fuel as a consequence of mechanical weeding. Contrary to the literature, we could not identify generally higher economic profitability of agro-ecological farms.

Although the application of the SAT was affected by practical challenges, the combination of approaches enabled an assessment of the status quo across different farming systems in Europe. In turn, this made it possible to identify general areas which could be improved, such as the need for a greater emphasis on integrating biodiversity conservation efforts into agricultural policy. The results also provide indications of prospective benefits of practices such as composting which could be promoted under the future Eco-schemes.

The assessment approach used in this study was characterised by its analytical strengths. However, there were challenges in applying the tools in the case studies. In subsequent applications, the tools could be improved by better integrating system boundary definitions and cut-off criteria for farm-level assessments. Given the advantages of combining different SATs, we identified the need for standardisation of the exchange of data between tools, which would facilitate improvements in future combined assessments.

In addition, a future study should explore the potential of including the combined assessment into existing, representative monitoring systems such as FADN. By implementing such improvements, the broad and interdisciplinary approach of the combined sustainability assessment provides results which can be of direct relevance for informing the development of policy and measures in national and regional agricultural and environmental strategies.

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Supplementary materials

This article has two supplements attached:
S1: Overview of SAT indicators
S2: Case Study Report Structure

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